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Compact forced simple-shear sample for studying shear localization in materials

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ABSTRACT

A new specimen geometry, the compact forced-simple-shear specimen (CFSS), has been developed as a means to achieve simple shear testing of materials over a range of temperatures and strain rates. The stress and strain state in the gage section is designed to produce essentially "pure" simple shear, mode II in-plane shear, in a compact-sample geometry. The 2-D plane of shear can be directly aligned along specified directional aspects of a material's microstructure of interest; i.e., systematic shear loading parallel, at 45°, and orthogonal to anisotropic microstructural features in a material such as the pancake-shaped grains typical in many rolled structural metals, or to specified directions in fiber-reinforced composites. The shear-stress shear-strain response and the damage evolution parallel and orthogonal to the pancake grain morphology in 7039-Al are shown to vary significantly as a function of orientation to the microstructure.

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1. Introduction

Unstable deformation of ductile metals and alloys subjected to complex loading paths and/or high strain rates is frequently associated with shear rupture (shear localization or shear bands) when the failure surface in the material is close to the plane of maximum shear stress, as opposed to void nucleation, growth, and coalescence. The development of predictive constitutive descriptions of strength, and thereafter damage-evolution and fracture models, requires a detailed understanding of the correlated effects among microstructure, loading conditions, and finally anisotropy, as many engineered materials possess orientation-dependent mechanical properties. The stability of plastic deformation in a given metal alloy, which depends on physical (heat capacity, thermal conductivity, thermal softening) mechanical (stress state, temperature, strain rate) and material/microstructural factors (e.g., crystallographic texture, grain morphology and shape, dislocation density and distribution, microstructural and phase stability) affect the ability of a material to deform homogeneously versus exhibiting a propensity toward inhomogeneous shear localization, has been the subject of numerous reviews and archival research studies over the past 6 decades [1–36]. The majority this research has focused on thermally-assisted mechanisms driving shear localization, i.e., adiabatic shear localization, of relevance to ballistic penetration [1,37,38], impact [2], and crashworthiness [2], high speed machining [2], and forming and manufacturing mechanics [2]. Accordingly, research emphasis has been placed on quantifying the mechanical and metallurgical characterization of shear bands, such as local strain, temperature, hardness distribution, and products inside shear bands [25,36].

A wide spectrum of test techniques and test sample geometries have been developed to examine and quantify the shear propensity of materials [39]. An in-depth description of the advantages and disadvantages of the various techniques is given in the book "Adiabatic Shear Localization" by Dodd and Bai [39]. Developed shear-loading techniques for metallic materials include: 1) torsion testing [40], 2) hat-shaped samples [12,41], 3) dynamic compression testing [42], 4) compression/shear testing [43], 5) cylinder expansion and collapse testing [44–46], 6) punch testing [47], 7) indentation testing [48], 8) double-shear specimen testing [49,50], 9) single-edge and double-edge specimens [51], 10) shear-compression testing [52], 11) simple-shear testing – a modification of ASTM B831 for sheet materials [53,54], and the eccentric notch shear specimen [55].

Given the propensity for adiabatic shear band formation during high-strain-rate loading, several experimental studies have

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particularly centered on the development of techniques to obtain compact sample geometries that can be readily loaded in high-strain-rate loading equipment such as split-Hopkinson Pressure/ Kolsky Bars, impact testing, drop-weight tests, and high-speed servo-hydraulic platforms. It is also of interest to have these dynamic loading tests conducted over a range of temperatures, and in a manner by which temporal shear-stress/shear-strain quantitative data can be obtained [39]. To achieve high shear rates under dynamic and/or impact loading conditions, several of the above mentioned specimen geometries have been devised such that linear displacement applied to the sample exterior boundary is transitioned into local “principle shear deformation” within a gage section of the specimen. One such forced shear sample, termed the “top-hat” specimen was originated by Hartman, Kunze, and Meyer [41] and Meyer and Manwaring [12] and thereafter further developed by several investigators [23,25,56]. This sample design has seen wide application due to its compact geometry making it readily amenable to testing on quasi-static, intermediate strain-rate testing platforms, and using split-Hopkinson/Kolsky Pressure Bars [57,58]. In addition, the ‘top-hat’ sample design has been modeled using finite-element methods, where the modeling results have been shown to positively compare with experimental results [58,59].

The small, compact nature of the ‘top-hat’ design has the advantages of: 1) readily facilitating testing at various temperatures within different testing platforms, 2) enabling studying shearing propensity in “small” cross-sections of material, such as through-thickness loading in the wall of cylindrical pipes or thin plates, and 3) through modification of the sample dimensions facilitate systematic variation of the magnitude of the compressive and shear loading components experienced within the cylindrical shearing section [60]. The “top-hat” design incorporates a slight overlap between the hat section and the cylindrical ‘brim’ portion that results in a mixed loading stress state within the cylindrical shear loading zone, combining both shear and compressive stresses. This design helps to restrain Mode I crack initiation along the shear localization zone.

However, several significant issues regarding the ‘top-hat’ sample geometry remain unresolved. First, due to the overlapping nature of the shear region in the sample design, during testing the shearing surface rotates during testing. In addition, there is a reduction of the shear conical area during the shear deformation making quantitative determination of the shear stress in the shear section difficult or impossible to achieve.

The second complexity with the ‘top-hat’ sample design is the radial expansion of the ‘brim’ portion of the hat-shaped specimen during testing. The inclined-shearing zone in the ‘top-hat’ sample is subjected to both compressive and shear loading components. While assumptions can be made to estimate the magnitude of the compressive stress on the shear stress behavior, and although the sample does allow examination of shear band formation in the absence of tensile failure, there remains no definitive way to both completely remove the bending moment within the sample nor quantify the shear strain evolution during the forced shear loading [23,59]. In estimating the shear stress, both the reduction of the shear area and the rotation of the shear direction were considered in the decomposition of the total force [23]. The estimation takes into account the fact that the overlapping shear region of the hat-shaped specimens leads to an additional hoop expansion of the cylindrical ‘brim’ that impedes a correct estimation of the load applied for the real shear deformation. Due to this fact, a fraction of the total input energy is allocated to expand the cylindrical ‘brim’, and this fraction varies as a function of the displacement in the estimation [23]. The qualitative estimation of the shear stress is further complicated if the metal or alloy is crystallographically textured as the yielding and work-hardening behavior around the circular shearing zone varies.

Third, due to the cylindrical or toroidal shear section being loaded in a “top-hat” specimen, systematic investigation of the shear response and/or shear band evolution correlated in crystallographically or morphologically anisotropic materials is not possible as isolated direct alignment of a planar shearing section in the specimen to a specific planar direction aligned to the microstructure cannot be achieved [61]. This is analogous to easy shearing of wood parallel to its grain compared to orthogonal to the grain (much harder to do) versus punching out a round plug in the same piece of wood, which represents an average shearing response akin to that obtained using a “top-hat” sample in metallic materials.

Additional forced shear loading techniques have been developed by Klepaczko using a modified double-shear specimen [50,62], direct impact-loaded pre-notched plate specimens by the Cal Tech group [63], and pressure-shear impact testing developed by Clifton et al. [64]. The double-shear specimen design subjects a material to a complex stress-state across the shearing zone surface as well as also lacking the ability to tie the shearing zone directly to a specific 2D loading plane within a material microstructure as discussed for the “top-hat” sample design due to its cylindrical shearing zone. The direct shock plate impact geometry facilitates a direct means to Mode II loading, but relies on impact loading to achieve this, and is therefore not amenable to testing across a spectrum of strain rates. This sample requires a significantly larger (200 × 100 × 6 mm) sample size making it impractical for testing many material product forms, and cannot be readily aligned with small-scale microstructural features.

The pressure-shear impact test is designed to obtain shear waves in symmetric plate impact experiments [64]. Limitations include, as with other wave propagation experiments, that: 1) the constitutive relations between stress, strain, and strain rate is not obtained directly, but must be inferred by comparison of the recorded wave profiles with those predicted for various constitutive models, 2) the testing is limited to fine-grained materials because the grain size must be small compared to specimen thickness to ensure that a representative average polycrystalline response is measured, 3) the experiments are lengthy and expensive because of the time required for sample preparation, and 4) the sample should be soft compared to the anvil plate material used to impose the deformation so that the anvil will remain elastic under the impact loading conditions of the experiment [65].

Rittel et al. developed an alternate shear-loading specimen geometry by which a shear dominant field is applied to a gage section through compression loading, either quasi-statically or dynamically, termed the shear compression specimen (SCS) [52,66–69]. An approximation of the stress state within the shearing zone of the SCS sample design has been modeled analytically [67] and simulated using finite-element modeling [52,66]. This sample design also offers a compact geometry that can be utilized in studying shear localization over a spectrum of strain rates and temperatures if desired. However, this geometry does possess several complications. First, the SCS sample design does not constitute a “simple” shear loading stress state within the gage section, but is rather a three-dimensional stress state [52,66,68]. Second, potential bending moments are possible in the sample due to lateral frictional constraint in the motion of the loading faces in contact with the loading platform, which are a concern. An assumption of no lateral frictional constraint on the loading faces, such as in the case of high-rate loading in a split-Hopkinson Pressure Bar, remains problematic at best. Finally, during loading, this geometry brings the added complication of radial inertial effects of the sample motion under dynamic loading.

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